Seeing quantum mechanics: The role of quantum experiments

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The second quantum revolution has prompted not only research in quantum science and technology, but also research on how best to educate students who may enter this burgeoning field. Much of the conversation around quantum science education has focused on students' conceptual learning or skills desired by potential employers; there has been an absence of work understanding how laboratory courses and experiments contribute to undergraduate quantum education. To begin understanding the role quantum experiments may play, we surveyed instructors who implement experiments with single and entangled photons in undergraduate lab courses and found that one of the most important learning goals was to "see quantum mechanics in real life." To better understand this goal, we interviewed 15 of the surveyed instructors asking what seeing quantum mechanics means to them and why they believe it is an important part of students' education. We present emergent themes from a qualitative coding analysis of these interviews, which begin to elucidate how instructors think about seeing quantum mechanics and what learning goals instructors hope seeing quantum mechanics—and working with quantum experiments more generally—will help students achieve.

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I. INTRODUCTION

The field of quantum information science and technology (QIST) is booming—governments are investing significant amounts of money in the field [1, 2], industry is developing numerous commercially available quantum products [3], and new quantum education programs are being created [4–6]. Likewise, physics education has followed this trend with a recent push to examine the current state of QIST education [5–10] and investigate what skills and knowledge this new quantum workforce will need [11–13], adding on to the existing body of literature studying students' conceptual understanding of quantum mechanics (e.g., Refs. [14–16]). Absent in much of this discussion is the role that instructional labs can play in students' quantum education.

There are many possible learning goals students may achieve in lab courses, including reinforcing conceptual learning, acquiring lab skills, and developing an understanding of the nature of experimentation in physics [17]. Prior research, focusing primarily on introductory labs, has found that labs are not always effective at reinforcing physics content [18], but can teach students expert-like experimentation practices, attitudes, and beliefs when the labs focus on experimentation skills [19–21]. Compared with introductory physics courses, quantum mechanics is often considered to be very mathematical [22–24], counter-intuitive [25, 26], and difficult to relate to the real world [27, 28]. Although these characteristics may be true of other concepts covered in beyond-first-year lab experiments, prior work studying students in theoretical quantum mechanics courses has found that students' epistemological beliefs [28] and views about measurement uncertainty [29–31] vary between quantum and classical physics contexts. It is therefore important to understand what students are learning from quantum labs and what resources are necessary to achieve those goals, so they can be accomplished as equitably as possible.

To investigate the role quantum labs have in educating the next generation of physicists, we began a project studying a set of experiments using heralded and entangled photons to demonstrate some of the counter-intuitive quantum concepts, such as single-photon interference and entanglement. An entire sequence of quantum optics experiments, often referred to as single-photon experiments, can be performed with equipment similar to that used in modern research labs. These experiments have been the subject of numerous articles describing how to use them in undergraduate lab courses (e.g., Refs. [32–34]) and have been supported by the Advanced Laboratory Physics Association (ALPhA) [35]. Between 2010 and 2021, 126 instructors have participated in the workshops (Immersions) hosted by ALPhA that teach the instructors how to set up the experiments, and around 100 institutions have bought some of the required equipment through ALPhA at a discounted price with many more on a waitlist. Because of the prevalence of these labs within the advanced labs community and the lack of research conducted on their efficacy to date, we surveyed 28 instructors of courses who use these experiments to learn more about how they use the experiments and their desired learning goals. We found that 86% of the respondents indicated that, for these experiments, the learning goal *seeing quantum mechanics in real life* was *very important* and the rest said it was *somewhat important*.

In order to better understand what instructors mean by "seeing quantum mechanics," we interviewed 15 instructors of the surveyed courses and performed a qualitative coding analysis of their interviews. Although we initially set out to uncover instructors' definitions of seeing quantum mechanics and why that was important to them, we found that instructors often struggled to define this learning goal. However, the instructors were enthusiastic to discuss this topic and brought up many interesting ideas surrounding seeing quantum mechanics in labs. In our analysis, we focused on these general emergent themes from the instructor interviews leading to our research question: *How do instructors think about seeing quantum mechanics in a lab?* We expect this work to help instructors by providing a framework for discussing seeing quantum mechanics as a learning goal for quantum lab experiments, give researchers a starting point for studying what quantum experiments can uniquely teach students, and stimulate a conversation in the community about the role of labs in quantum education.

II. METHODOLOGY

We sent out the initial survey to 170 instructors, all of whom had taken or taught an ALPhA Immersion workshop about the single-photon experiments or had purchased equipment for these experiments through ALPhA. We additionally posted the survey on the ALPhA Slack channel. We received complete survey responses from 28 instructors, and of those 26 said they would consider partnering with us in the future. We emailed all 26 of those instructors inviting them to participate in an interview and ended up with 15 participants. Of the interviewed instructors, 13 were men and 2 were women. Fourteen of the instructors self-identified as white with two also identifying as Hispanic. The other self-identified as South Asian. These instructors teach primarily Advanced Lab and Quantum Mechanics courses for junior and senior physics majors at 15 different institutions. Out of these institutions, four are Ph.D.-granting institutions, four are Masters-degree-granting institutions, seven are 4-year colleges, and one is a Hispanic-Serving Institution.

We conducted semi-structured interviews over Zoom and took a phenomenographic approach to coding the transcripts. The interviews lasted between 49 and 69 minutes. Each contained sets of questions about the course context, how the instructor defined seeing quantum mechanics and why it was important, if the instructor thought students in their course saw quantum mechanics, and other goals of using the single-photon experiments (e.g., excitement/motivation, lab skills, etc.). We performed a thematic coding analysis [36] , and our codebook consists of emergent themes related to the idea of seeing quantum mechanics that appeared in multiple interviews. After two of the authors created the codebook through an iterative process, the third author performed an interrater reliability check with a Cohen's kappa coefficient of 0.7, which is considered substantial agreement [37]. The main discrepancy between the coders was for a single code, which was redefined and divided into three separate codes. Excerpts coded into these three categories were then reviewed and agreed upon by the research team.

III. RESULTS

Here, we present the emergent themes from the instructor interviews, divided into two categories determined by the authors after the coding process:

- Seeing quantum mechanics may include...
  - A1. *Experiments that are described by quantum (not classical) physics*
  - A2. *Not literally seeing quantum objects*
  - A3. *Seeing experimental effects, results, or statistics*
  - A4. *Seeing and understanding experimental apparatus*
  - A5. *Interactions with the experiment*
  - A6. *Understanding theory behind the experiment*
  - A7. *Clear results that require little interpretation*
- Seeing quantum mechanics can / can help students...
  - B1. *Believe quantum mechanics describes the physical world*
  - B2. *Gain familiarity with quantum mechanics*
  - B3. *Improve conceptual understanding*
  - B4. *Think about philosophy of quantum mechanics*
  - B5. *Generate excitement and motivation*
  - B6. *Learn about topics of technological and societal importance*
  - B7. *Make quantum more accessible*

The first theme (A1) points out the seemingly obvious idea that seeing quantum mechanics depends on seeing something that can only be described by quantum mechanics. Some instructors mentioned that quantum mechanics is needed to explain the experimental phenomena or, similarly, that classical mechanics is insufficient, while other instructors emphasized the need for model testing and directly comparing results coming from both classical and quantum models. It is interesting to note that what instructors consider "quantum" may differ. For example, one instructor discussed an experiment that used an attenuated laser to send on average one photon at a time into an interferometer and stated that seeing interference from those photons counted as seeing quantum mechanics, even though this can be described by the classical theory of light. However, he also thought that the single photon interferometer using an actual single (or heralded) photon source, as for the studied experiments, was "even better."

Other themes in this first category relate to what is seen and what is not seen in quantum experiments. Some instructors acknowledge that they are not actually seeing the quantum objects, e.g., photons (A2). Many instructors instead discuss seeing experimental results, statistics, or "effects" (A3). Others note that part of seeing quantum mechanics is students being able to physically see a large portion of the experimental apparatus (part of A4). When asked what caused students to see quantum mechanics while working with the single-photon interference experiment, one instructor discussed the way the students were able to see both physically separated paths the photon takes: *"The fact that you can look down at the physical setup and say here's one path and here's another path. And those are two separate paths and therefore they recombine."* She went on to compare this with creating a superposition polarization state and ended by explaining how much clearer it is to students when they can point to the two parts of the apparatus that represent the different parts of the superposition: *"So I do think that the physical layout, the physical objects they can point to, would be significant."*

Even though many instructors used the phrase seeing quantum mechanics throughout their interviews, the majority viewed "seeing" as requiring additional interaction with the experimental apparatus (A5). After being asked what seeing quantum mechanics means to him, one instructor stated plainly: *"So I'll just start with the first word seeing. To me, that means doing an experiment..."* Different instructors cared about different aspects of interacting with or performing an experiment. Some instructors focused on physically interacting with the experimental apparatus and getting to "play with it," while another emphasized that the important part was the students needing to "make decisions," which could even happen in a remote version of the lab designed for the COVID-19 pandemic.

However, simply seeing or doing an experiment was not enough for some instructors who expressed that students must also understand what was happening. Instructors, particularly those who discussed seeing the experimental apparatus, often focused on students understanding how the different parts of the apparatus worked (part of A4). Others focused on students fully understanding the theory that underpinned the experimental results (A6). When comparing two different experiments done with a similar apparatus, one instructor expressed that the experiment where students could "own" the experiment and *"understand [it] from the beginning to the end"* was preferred because then *"...there's nothing mysterious. You understood every single step of the way..."* and claimed that *"...that's seeing quantum mechanics. That you owned the derivation and the answer and you may still think there might be something not true and then you do the experiment and then it verifies it."*

Other instructors take a different approach—emphasizing that students are more likely to see quantum mechanics if the experimental results are very clear and do not involve additional steps of interpretation (A7). When asked what seeing quantum mechanics means to him, one instructor said: *"Okay yeah I mean to me it means seeing quantum phenomena that are very clear in experiments... you don't have to do a lot of mental interpretation to see the quantum phenomena illustrated."* This was followed by the example of the single-photon interference experiment where students can see interference fringes *"in the first ten seconds of measurement"* that only occur because of quantum mechanics. There are different ways for students to understand that they are seeing a quantum effect, and some instructors emphasized that students need to understand all the theory, while others focused on the idea of demonstrating effects that require fewer mathematical steps.

The other category of emergent codes includes possible outcomes the students may achieve, such as understanding and believing that the theory of quantum mechanics manifests in the physical world (B1). Many instructors mentioned how "theoretical" quantum mechanics is and how they want their students to realize it *"describes the real world."* Instructors often focused on how seeing the experimental results makes students believe them *"because it has to be happening."* They used phrases like "real world" or "reality," although almost all of them were referring to lab experiments. One instructor instead brought up the idea of wanting students to understand the many places quantum mechanics occurs in their everyday lives: *"I would not say that it's hard to see quantum effects, but I would say that it's hard to realize that you're seeing quantum effects if you've lived the classical way. So you know I can say oh look quantum everywhere, right, like you're not decaying, your atoms are stable, that's a quantum effect. But obviously the average student doesn't think about it that way."*

Another theme that emerged is how seeing quantum mechanics can give students a sense of familiarity with quantum ideas and help them realize that quantum is not as weird or mysterious as they thought (B2). There were many times instructors mentioned this idea of familiarity without specifying exactly what it would help students understand better. For example, when asked why seeing quantum mechanics was important, one instructor said: *"Quantum mechanics is so mathematical and so abstract. Anything that you can do to make it more hands on, more concrete, I think is a good thing... and that then gives you more confidence in the whole structure itself of quantum mechanics... it is so abstract, that to feel more comfortable with it, to have more confidence in it, to be able to do an experiment that confirms some of the predictions, is, I think, a good thing."* Many other quotes coded in this category contained the word "intuition," which is often brought up when discussing quantum mechanics but is defined differently by different people [25].

Instructors also hoped that seeing quantum mechanics would help students improve their understanding of quantum concepts (B3). By gaining exposure to the experiments, students might think about quantum concepts differently, which could clear up any misconceptions they may have had from non-lab components of quantum mechanics courses. Additionally, some instructors mentioned that doing the experiments forced students to think about different philosophical ideas and interpretations in quantum mechanics (B4). For example, when asked what seeing quantum mechanics means in the context of these single-photon experiments, one instructor said: *"... everyone has a little slightly different philosophical way of thinking about this, but I think the question of whether or not you view photons as real physical objects or as artifacts of measurement is also an important thing to challenge participants to think about."*

Two of the emergent themes relate to student excitement and future careers. Many instructors mention that quantum experiments generate excitement among the students, possibly motivating them to study more in their non-lab courses or pursue physics as a career (B5). Some of this excitement is related to the way that quantum mechanics has come into the public awareness due to technological applications (such as quantum computing) and through pop culture (B6). Learning experimentally about quantum concepts can help students in future careers, make them feel excited or proud because they have a deeper connection to these complex ideas, and allow them to take their new knowledge and educate the general public. When asked what was his learning goal related to student excitement and motivation, one instructor said: *"It's all about interpretations of quantum mechanics, which even the general public is fairly excited about. And you know, we see these sort of sci-fi versions of the quantum realm, and I think students feel proud that these sort of pop culture references have a deeper resonance for them. Like they can enjoy the pop culture aspect, but then they also understand more deeply why Bell's theorem is a rigorous theorem and what an experiment involves."*

The last theme (B7) discusses how seeing quantum mechanics can make the field of quantum mechanics, which is often thought of as being particularly difficult to understand, more accessible to a wide variety of students. One instructor, when discussing why excitement or motivation was important clearly differentiated between students who were excited just by the theory and students who were intimidated by the theory, but were able to get around that by working with the experiment: *"There's a native excitement when you start talking about quantum if the student has access to—for some students they don't need access to laboratory equipment, but I think for the students that are in that 60% where they're like I'm interested in quantum but I'm a little bit intimidated by the mathematics that I often see associated with it. My experience is that when they're exposed to something like that, they get really excited."* Another instructor discussed how these experiments *"opened up quantum mechanics for folks who were more interested in the applications and who liked more experimental physics."* Likewise, one other instructor felt that by working with quantum experiments, students realized that they were capable of doing work in a field of active research.

Some additional, un-coded, themes arose during these interviews that did not depend on the experiments being quantum. Some instructors discussed how students learned optics skills while working with the quantum experiments, which could happen equally as well with non-quantum optics experiments. Other instructors mentioned the excitement from "cool" lab equipment, which also is not unique to quantum experiments, although more complicated experiments often necessitate more interesting apparatus. Other instructors mentioned the general idea that experiments are an important part of physics, and how seeing quantum mechanics is an instance of that with one of the "pillars" of physics. The interviewed instructors gave a mix of responses to whether or not seeing quantum mechanics is more important than seeing other areas of physics.

IV. DISCUSSION AND CONCLUSION

The first category of emergent themes (A1–7) demonstrates that there are a variety of ways instructors want students to interact with quantum experiments, and even though some instructors use the word "seeing," many want students to have a deeper interaction or understanding that goes with it. Instructors think about seeing quantum mechanics in terms of different subsets of these codes, which could lead to varying methods of incorporating the experiments into their courses. The first category contains seemingly contrasting codes (A6 and A7) that both relate to students understanding the results, but one from doing a lot of calculations and the other from not needing to do much additional theoretical work. Future research could look at how different parts of seeing quantum mechanics contribute to various student outcomes.

The second category of themes (B1–7) covers a wide range of desirable student outcomes, some of which are particularly salient for quantum mechanics, while others are similar to goals for all lab courses. Almost all of these codes could be seen as instances of reasons why physics experiments are important in general. For example, many of our findings are similar to the emergent codes from students responses to a question about the purpose of physics experiments in Ref. [38]. However, many of these codes (e.g., B1, B2, B4, B6, and B7) also depend on the way quantum mechanics is often perceived as being particularly theoretical or difficult and not being evident on the macroscopic scale, as well as due to the current hype surrounding quantum technologies [39, 40]. Many of the interviewed instructors hope quantum experiments will improve their students' conceptual understanding of quantum mechanics. Recent work has found that introductory labs focused on reinforcing concepts do not always improve students' conceptual understanding and may even negatively impact students' views of experimental physics [21, 41]. However, this may not be the case in beyond-first-year labs focused on quantum mechanics. Further work is needed to investigate if the complexity of quantum mechanics and quantum experiments allows for students to learn and reinforce concepts in ways that do not always occur in introductory labs.

As this new push towards quantum education continues, care needs to be taken to ensure that it is as equitable as possible. One of our emergent themes on making quantum more accessible (B7) refers to part of this idea. Other studies have shown that excitement to learn quantum mechanics can inspire students to study physics, but some students get turned away when they first take a quantum class because of the emphasis on calculation [23]. Experiments may help open up the field of quantum mechanics to students who do not have a solid mathematical background [26] or strong self-efficacy [42]. However, the quantum experiments we focused on in this work are very resource intensive, requiring significant amounts of time and money to set them up, and not all institutions have the necessary resources at their disposal. It is therefore important to further study which goals of the experiments can be accomplished in a less resource-intensive way and which require the full experimental set-up. Similarly, understanding how "quantum" an experiment needs to be to achieve the desired learning goals could be important, as it may drastically reduce the cost of the experimental equipment and time it takes to set up the experiment. Additionally, there are other accessibility concerns not addressed in this work. We focused on the idea of seeing quantum mechanics, but not all students are able to physically see or participate in a lab [43]. Future research should investigate how the student outcomes presented here can be attained by all students.

This study provides potential motivation for incorporating quantum experiments (or other ways to achieve the same learning goals) into the physics curriculum, but it is limited by being focused on one specific kind of experiment. Because this study came about as part of a larger project investigating the efficacy of the single-photon experiments, both the sample of instructors, as well as the kinds of responses they gave, are influenced by this specific set of experiments. All of the instructors were teaching with these quantum lab experiments, so they (or a predecessor in their department) thought these experiments were important enough to be worth the cost. Additionally, although some instructors initially discussed the idea of seeing quantum mechanics more generally, most immediately started discussing it in the context of these experiments. The goal of this work is to demonstrate the possibility of various learning goals from working with quantum experiments, but care needs to be taken when generalizing these results to other quantum experiments. It would also be interesting to ask instructors of theory courses their views on this idea of seeing quantum mechanics and if they also believe there are some learning goals that can only come about from interacting with experiments.

This is just the first step of a larger project examining the efficacy of the single-photon experiments. We plan to further analyze the instructor interviews and have begun interviewing students to see how they think about seeing quantum mechanics and if they believe they have achieved some of the desired outcomes. We hope this work will lay the groundwork for further studies of quantum labs and will help us better understand the role quantum experiments can play in preparing students for the quantum workforce and other careers.

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